Phase Transformation of an Austempered Ductile Iron during an Erosion Process

Fei-Yi Hung*, Li-Hui Chen and Truan-Sheng Lui

Department of Materials Science and Engineering, National Cheng Kung University, Tainan, Taiwan 701, R.O. China

Ductile iron specimens of ~3.5 mass% C and ~2.8 mass% Si were austempered at 420℃ for 0.5 h~24 h. These upper bainitic austempered ductile iron (ADI) specimens were 90°-eroded by Al2O3 particles of ~275 μm grit size under the average particle velocity of 73 m/s to understand phase transformation at the erosion surface. According to the experimental results, the retained austenite content and the carbon content of bainitic ferrite decreases through phase transformation during erosion. After erosion, the retained austenite and the high carbon content bainitic ferrite form e-carbide, another carbide and ferrite. The other austempering carbide of the remaining matrix also transforms into e-carbide in the erosion process.

(Received May 31, 2004; Accepted August 5, 2004)

Keywords: erosion, spheroidal graphite cast iron, austempered ductile cast iron (ADI), phase transformation, retained austenite, e-carbide

1. Introduction

Most of the available literature indicates that the retained austenite in ADI undergoes strain-induced martensitic transformation which results in fracturing during deformation processes.1–4) Reports on ADI wear, including abrasive wear,5,6) sliding wear,7) rolling wear8) and gear-wear,9) reveal the common result that the high carbon austenite content will decrease through transformation into the martensite phase. This raises the hardness of the eroded-surface and reduces the fracture toughness of the material. For erosion wear, the reports only discuss the erosion rate for ADI that has the same chemical composition and heat treatment condition.10,11) Further, the reports also infer that the retained austenite transforms into martensite by erosion. The mechanism of erosion induce phase transformation has not yet been ascertained. In the current study, the phase transformation of upper bainitic ADI during erosion by Al2O3 particles was investigated.

2. Experimental Procedures

The austempering time of upper bainitic austempered ductile iron is divided into Stage I (short tempering time) and Stage II (long tempering time).4,12) After austempering for a short period of time, the low carbon concentration austenite in Stage I ADI forms martensite, retained austenite and bainitic ferrite. However, the structures of Stage II ADI include bainitic ferrite, retained austenite and carbide. The ADI used in this experiment contains 3.45 mass% carbon and 2.82 mass% silicon (composition data is shown in Table 1). The ADI specimens were austenized at 930℃ for 1 h and austempered at 420℃ for different lengths of time, then water quenched at room temperature. According to previous results, ADI austempered at 420℃ for 0.5 h contains no martensite. Hereafter, the upper bainitic ADI specimens will be designated according to their austempering time as UB0.5 h, UB1 h, UB2 h, UB3 h and UB24 h.

A sandblasting type erosion tester was used for the wear test. Angular Al2O3 particles (275 μm mean grit size, see Fig. 1 for the morphology) were selected as the erodent. They were ejected by a compressed air with a flow pressure of 3 kgw·m⁻² (0.29 MPa) and a flow-rate of about 1 g·s⁻¹. The impact is fixed at 90° from the sample surface (normal impact). Estimated by high-speed single-exposure photograpy, the average particle velocity was 73 m·s⁻¹.13)

Each specimen was impacted with 500 g of the Al2O3 particles. Before erosion and after erosion, an image analyzer and the X-ray diffraction were used for quantitative analysis of the microstructure. The Cu-Kα standard (λ = 1.5403 nm) was used for X-ray diffraction. The scanning angle was varied from 30° to 90° and the scanning velocity was 1°·min⁻¹. The retained austenite content of matrix was measured by the X-ray diffraction before and after the erosion test. The X-ray diffraction was estimated by using the integral method on the γ (200), γ (311) and α (211) peaks. In order to understand the characteristics of the matrix before

<table>
<thead>
<tr>
<th>Table 1 Chemical composition (mass%).</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
</tr>
<tr>
<td>ADI 3.45</td>
</tr>
</tbody>
</table>

*Corresponding author, E-mail address: fyhung@mail.mse.ncku.edu.tw
and after the erosion process, the structures of the affected regions of the ADI samples were observed by TEM.

The TEM specimen was obtained from the eroded ADI. The bottom of this specimen was cut to form a 1 mm plate. To reduce the effect of cutting heat, a low speed cutter was used. The plate was polished to a thickness of ~40 μm (measured from wear surface to the bottom layer). This specimen was further reduced in thickness to 3 μm through ion milling to allow the wear zone to be observed by TEM (The type is JEOL-JEM-3010). For comparison with the eroded sample, the microstructure of the original ADI specimen (no erosion wear) was also confirmed by TEM. The milling processes of the eroded specimens and uneroded specimens were similar. During TEM operation, the voltage value was set at 300 kV.

3. Results and Discussion

3.1 The structures and characteristics of ADI before erosion

Figure 2 shows the microstructure of the ADI specimens. It can be seen that the retained austenite (indicated by the arrow γ) content decreases with increased austempering time. Table 2 shows the opposing trends in retained austenite content and matrix hardness with tempering time. The TEM results from the UB0.5 h specimen shown in Fig. 3, the dark area was retained austenite phase between ferrite laths (white regions). According our observations, the martensite was not found in austenite phases (include near-grain boundary). Besides, the UB0.5 h tempering carbides also have not detected in ferrite/austenite and ferrite/ferrite interfaces. The UB0.5 h specimen can be considered to be initial Stage II, it’s matrix is composed of retained austenite with high carbon content and bainitic ferrite.

Increasing the austempering time beyond 0.5 h will cause the high carbon content retained austenite to decompose into bainitic ferrite and carbides. These carbides raise the matrix hardness. The TEM observations of UB3h in Fig. 4 prove that there are particle carbides and needle ε-carbides in the α phase region.

| Table 2 Hardness and Vol% (R.A.) before erosion test. |
|---------------------------------|----------------|----------------|----------------|----------------|
| ADI | UB0.5 h | UB1 h | UB2 h | UB3 h |
| vol.% (R.A.) | 29.4 | 27.2 | 16.8 | 2.1 |
| HRC | 26 | 27 | 29 | 31 |

Vol% (R.A.): the amount of retained austenite before erosion. HRC: rockwell hardness.
3.2 Erosion induced phase transformation

Figure 5 shows the volume content of retained austenite in specimens after erosion. For comparison, the change in retained austenite content before erosion (the data in Table 2) is also shown in Fig. 5. These two data sets indicate that the retained austenite undergoes phase transformed during particle erosion. The X-ray diffraction patterns of the as-austempered and eroded specimens are illustrated in Figs. 6 (a) and (b). Regardless of the austempering condition, no carbide peaks can be found in Fig. 6(a). As a consequence, Fig. 6(b) confirms the formation of ε-carbides during particle impingement. After erosion, observations of the UB0.5 specimen wear surface indicated ε-carbides in the α phase region as shown in Fig. 7.

When Initial Stage II ADI (0.5 h) is compared with Final Stage II ADI (3 h) before erosion (see Fig. 3 and Fig. 4), Final Stage II ADI contains not only ε-carbides but also fine
particle carbides (see Fig. 4). It is worth noting that the amount of austempered carbide increases with increased austempering time. Figure 3 reveals no carbide in the UB0.5h specimen matrix before erosion. After erosion, the UB0.5 hr’s $\varepsilon$-carbides was found in the $\alpha$ phase regions (see Fig. 7). This result confirms that the phase transformation occurs during the erosion process. Figure 5 also shows that the retained austenite content decreases after erosion. This is due to erosion induced phase transformation of the retained austenite. According to Fig. 5, after erosion, the retained austenite content of the UB3 h decreased by 2.1 volume percent (vol%) and the retained austenite content of the other specimens is reduced by roughly 12.5~17 vol%. From these results and Fig. 6 it can also be seen that through the variation in retained austenite content of UB3 h is much smaller than that of the other specimens, the $\varepsilon$-carbide content is similar in all cases.

Figure 5 shows that the original $\sim2$ vol% retained austenite of the UB3 h specimen has been completely transformed. However, the resolution of the X-ray diffraction is not high enough to identify carbide generated from only $\sim2$ vol% retained austenite. Therefore, the spectra of $\varepsilon$-carbide revealed in Fig. 6(b) for UB3 h implies that erosion induces phase transformation not only in the retained austenite, but in other phases. To give supporting evidence for this, cast iron was austempered for 24 h to eliminate any retained austenite and then eroded. The X-ray diffraction patterns, which are given in Fig. 8, indicate the formation of $\varepsilon$-carbide upon particle erosion. Which matrix phases (include bainitic ferrite and austempered carbide) other than the retained austenite can be transformed during the erosion process is an important question.

Neither the uneroded UB3 h specimen (Fig. 6(a)) nor the uneroded UB24 h specimen (Fig. 8) indicates the presence of carbide. But Fig. 4 shows that UB3 h has other fine tempering carbides and needle $\varepsilon$-carbides in matrix. TEM analysis (not given here) has also confirmed that the UB24 h sample has similar carbides in the matrix. This indicates that the carbides

---

**Fig. 6** The X-ray diffraction patterns of ADI: (a) as-austempered and (b) eroded.

---

**Fig. 7** Transmission electron micrograph and SADP of UB0.5 h specimen after erosion test: (a) BF image, (b) DF image and (c) SAED pattern of $\varepsilon$-carbide.
in uneroded specimens subjected to long austempering time can not be found by X-ray. XPS and TEM analyses were performed to improve understanding of the phase transformation.

For the UB24 h specimen, the XPS analysis only revealed the carbide peak (erosion induced) in eroded ADI (Fig. 9). This evidence also reveals that the austempered carbide can’t be detected by XPS. For the UB24 h specimen after erosion, there are \(\varepsilon\)-carbides in the bainitic ferrite. However, the other austempering carbides can’t be observed easily as shown in Fig. 10. In the EDS analysis shown in Fig. 11, the carbon concentration in the UB24 h specimen before erosion is higher than equilibrium.\(^{12,14}\) The carbon concentration is even higher than that in the eroded specimen. Clearly, this higher carbon bainitic ferrite undergoes phase transformation to form low carbon bainitic ferrite and carbides during the erosion process. Consequently, in this current study, the erosion induces phase transformation not only in the retained austenite but also in the higher carbon bainitic ferrite.

Particle impingement can raise the temperature of the worn sample, which may lead to various phenomena such as whisker growth,\(^{16}\) recovery,\(^{17}\) and melting.\(^{18}\) Using testing conditions similar to those of the current study, we have also found that the temperature increase will dissolve the Mg\(_2\)Si
particles in T-6 treated Al 7 mass%-Si 0.3 mass%-Mg alloy. Judging from the above phenomena, the strain-induced martensite transformation of the retained austenite in ADI is unlikely to occur unless special care is taken to limit the thermal effect. Indeed, rather than martensite, $\varepsilon$-carbides were detected in the present study.

4. Conclusions

Based on the above results and discussion, the following conclusions can be drawn.

(1) The $\varepsilon$-carbides and other particle carbides can be formed in ADI specimen after a long austempering period. The volume percent of retained austenite and the carbon concentration of bainitic ferrite will decrease after particle erosion.

(2) During the $\text{Al}_2\text{O}_3$ particle erosion process, the retained austenite and high carbon bainitic ferrite will induce phase transformation to form the $\varepsilon$-carbides, other carbides and ferrite.

(3) The remaining matrix phases other than the retained austenite can be transformed into $\varepsilon$-carbides during particle impingement. Analysis indicates the formation of $\varepsilon$-carbides but not martensite.

Acknowledgements

This work was financially supported by the National Science Council of Taiwan, R.O.C. for which we are grateful (Contract No. NSC 92-2216-E-006-019).

REFERENCES